(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(54) Title: DIRECT OPTICAL FM DISCRIMINATOR
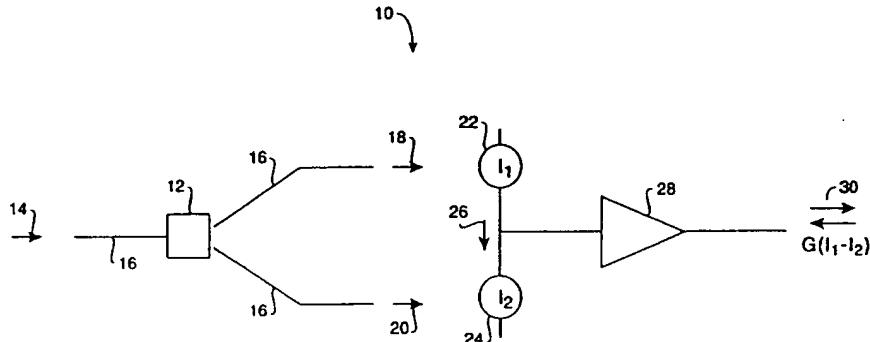
(57) Abstract: A method and apparatus for optical frequency modulation discrimination. An optical beam is split into a first optical beam and a second optical beam. A first photodetector is provided, the first photodetector providing a first current responsive to the first optical beam input thereon, the first photodetector having a first photodetector spectral response and being biased such that the first current is in a first direction. A second photodetector is also provided, the second photodetector providing a second current responsive to the second optical beam input thereon, the second photodetector having a second photodetector spectral response and being biased such that the second current is in the first direction. An input of a transimpedance amplifier is coupled to an output of the first photodetector and to an input of the second photodetector to provide an output of the transimpedance amplifier proportional to the difference between the first current and the second current. A first optical filter is provided to receive the first optical beam prior to incidence upon the first photodetector and a second optical filter to receive the second optical beam prior to incidence upon the second photodetector, wherein the first photodetector spectral response and the second photodetector spectral response are each broader than respective passbands of the first optical filter and the second optical filter to provide photocurrent vs. optical frequency characteristics determined by the respective first optical filter and the second optical filter.

DIRECT OPTICAL FM DISCRIMINATOR

FIELD OF THE INVENTION

This invention relates to the field of communications, and, in particular, to optical devices for
satellite communications systems.

BACKGROUND

Orbiting satellites are an important aspect of modern communication systems. Originally used
for "single-bounce" communication, with a signal going up from one place on the surface of
the earth and coming down in another, communication satellites are now being used to form
complex networks in space, with each satellite in the network being able to communicate with
many, but not all, of the other satellites. Optical intersatellite links, with their high directionality,
high energy efficiency, and tremendous information bandwidth, allow satellites to talk to one
another, and to transmit a much larger amount of information. Optical FM links, a new concept,
offer a way to transmit not only digital signals, but also analog signals, and to do this with a
much higher signal quality than was heretofore possible. However, effective optical FM links
have not yet been demonstrated primarily because of the lack of appropriate photonic
components, such as FM optical sources, limiters, and discriminators.

The only experimentally-proven discriminator that has appeared in the literature to date is a
Mach–Zehnder interferometer with a delay line in one branch, as discussed in the Journal of
Lightwave Tech., Vol. 10, 787–793, 1992 article by W.V. Sorin, et al, entitled "Frequency
Domain Analysis of an Optical FM Discriminator". However, the disadvantages of this
approach are twofold. First, the interferometer has a sin Δf response, instead of a desired Δf.
Although approximately linear for small frequency deviations, the response becomes nonlinear
for larger frequency deviations. Secondly, the delay line length, which can be several
centimeters, must be held constant to a small fraction of an optical wavelength. This requires
active and precise thermal control of the circuit. The size and weight of these controllers, and
the added complexity associated with them, are undesirable features for space–borne (e.g.,
satellite communication) systems, where size and weight are of paramount importance.

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U.S. Patent 5,742,714 issued to Byron teaches interferometrically combining two optical waves to produce an output intensity that can vary from zero (complete destructive interference) to unity (complete constructive interference). The variation of this intensity with wavelength gives a raised cosine response, identical to that produced by the delay–line discriminator of Sorin referenced above. In fact, the Byron device is an example of a delay line discriminator, with the delay being produced by the different positional reflections in the longitudinal filters. While the Byron device uses light, splitters and filters, the device cannot provide the high-linearity needed for the high-fidelity transmission of analog signals. The nonlinearity introduced by the Byron and other interferometric discriminators produces harmonic and intermodulation distortion that can seriously degrade signal quality.

Therefore, to help further realize optical FM inter-satellite links, there exists a need for an effective photonic device that allows one to directly convert excursions in optical frequency into variations in photocurrent, without the use of optical interferometry. The present invention provides a solution for such need by providing an optical FM discriminator with high linearity characteristics.

SUMMARY OF THE INVENTION

In accordance with the present invention, embodiments of an FM discriminator are provided which are highly linear with respect to frequency deviation. Such high linearity is of considerable importance for analog optical links since, as noted earlier, non-linearities introduce undesired harmonic and intermodulation distortion products which, being a form of noise, reduce signal quality. Further, the device in accordance with the present invention does not need the thermal control circuits and elements required by existing interferometric techniques.

In accordance with a preferred embodiment of the present invention a method and apparatus for optical frequency modulation discrimination is provided. An optical beam having a frequency ω is split into a first optical beam having a frequency ω and a second optical beam having a frequency ω. A first semiconductor photodetector is provided, the first photodetector providing a first current I_1 responsive to the first optical beam input thereon, the first photodetector having a first photodetector spectral response and being biased such that the first current I_1 is in a first direction. A second photodetector is also provided, the second photodetector providing a second current I_2 responsive to the second optical beam input thereon, the second photodetector having

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a second photodetector spectral response and being biased such that the second current I_2 is in the first direction. An input of a transimpedance amplifier is coupled to an output of the first photodetector and to an input of the second photodetector to provide an output of the transimpedance amplifier proportional to the difference between the first current I_1 and the second current I_2. A first optical filter is provided to receive the first optical beam prior to incidence upon the first photodetector and a second optical filter to receive the second optical beam prior to incidence upon the second photodetector, wherein the first photodetector spectral response and the second photodetector spectral response are each much broader than respective passbands of the first optical filter and the second optical filter, thus providing photocurrent vs. optical frequency characteristics determined by the respective first optical filter and the second optical filter. The first optical filter and the second optical filter, respectively, can provide Lorentzian line shapes. The first optical filter and/or the second optical filter are tuneable to adjust wavelength separation between the first tunable optical filter and the second tunable optical filter to obtain maximum linearity. The first optical filter and/or the second optical filter are tuneable to operate over a broad range of operating wavelengths. The first optical filter and the second tunable optical filter can be fiber–optic tunable Fabry–Perot filters and the first photodetector and the second photodetector can be high–speed semiconductor photodetectors, such as InGaAs semiconductor photodetectors.

In accordance with an alternate embodiment of the present invention, a method and apparatus for optical frequency modulation discrimination is provided wherein an optical beam having a frequency ω is split into a first optical beam having a frequency ω and a second optical beam having a frequency ω. A first photodetector is provided having a peak resonant absorption ω_1, the first photodetector providing a first current I_1 responsive to the first optical beam input thereon, the first photodetector being biased such that the first current I_1 is in a first direction. A second photodetector is also provided having a peak resonant absorption ω_2, the second photodetector providing a second current I_2 responsive to the second optical beam input thereon, the second photodetector being biased such that the second current I_2 is in the first direction. An input of a transimpedance amplifier is coupled to an output of the first photodetector and to an input of the second photodetector to provide an output of the transimpedance amplifier proportional to the difference between the first current I_1 and the second current I_2.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 shows in schematic block diagram form a first embodiment of the present invention.

Figs. 2A - 2B depict the response of two resonantly absorbing photodetectors centered at frequencies ω_1 and ω_2, respectively.

Figs. 3A - 3C depict differential current versus frequency deviation for three different frequency situations.

Fig. 4 shows a schematic block diagram for a second and preferred embodiment of the present invention.

Figs. 5A - 5B depict frequency passband of optical filters in accordance with the second and preferred embodiment of the present invention.

DETAILED DESCRIPTION

Referring to Fig. 1, an embodiment of the present invention is shown. Optical discriminator 10 includes optical splitter 12, which can be either a conventional 50:50 fiber optical splitter, (such as, for example, a Gould 22-1-0355-50-1120), or, for an unguided free-space beam, a bulk-optic 50:50 beam splitting cube (such as, for example, a Newport 05BC16NP.11), which receives the frequency-modulated optical beam 14, either guided by conventional single-mode or multi-mode fiber 16, or propagated as an expanded free-space beam. Optical splitter 12 divides optical beam 14 into two equal-intensity beams 18, 20. Each of these beams impinges upon respective photodetectors, 22, 24, one with a peak resonant absorption at ω_1, as depicted in Fig. 2A, the other at ω_2, as depicted in Fig. 2B. Photodetectors 22, 24 are biased (not shown) in such a way that the current flow is in direction 26. If the frequency of light beams 18, 20 coincides with the center of absorption of photodetector 22, then the current I_1 through photodetector 22 will be large, and the current I_2 through photodetector 24 will be almost zero. Because almost no current can flow through the photodetector 24 (i.e., it has been "optically" turned off), the entire current must flow into transimpedance amplifier 28, (such as, for example, an Avantek ITA-02070 for applications below 1 GHz), coupled to the junction of photodetector 22 and photodetector 24. Signal 30, which is generally described as $G (I_1 - I_2)$ where G is the gain of transimpedance amplifier 28, out of transimpedance amplifier 28 will thus be proportional to I_1,

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and will be positive. If the frequency of light beams 18, 20 is shifted so that it now coincides with the absorption maxima of photodetector 24, the reverse will occur, namely current flow is now out of transimpedance amplifier 28, not into it, so that output signal 30 will be proportional to current I_2 through photodetector 24, and will be negative. If the frequency of the light beams are changed to ω_0, equal currents will be generated by each detector, and the current will flow directly from one through the other, with none going into transimpedance amplifier 28. The amplifier output in this case will be zero. The optical discriminator embodiment of Fig. 1 thus amplifies only the difference in detector currents. Electrically speaking, it has high common–mode rejection. If the absorption profiles have Lorentzian lineshapes, then the equation for the differential current flow is given by

$$I_1 - I_2 = A \left\{ \frac{1}{(\omega_1 - \omega)^2 + \Gamma^2} - \frac{1}{(\omega_2 - \omega)^2 + \Gamma^2} \right\}$$

where ω_1 and ω_2 are the resonant frequencies of photodetectors 22 and 24 respectively and Γ is the linewidth constant which determines the frequency width of the absorption. As will be shown below, there is an optimum choice of parameters which leads to an amplitude versus frequency response function that is highly linear.

Referring to Figs. 3A - 3C, there is shown the differential current versus frequency deviation for three different cases, where $\Omega = (\omega_1 - \omega_2)/2$. The case depicted in Fig. 3A is the one with the highest linearity, and is realized when the linewidth parameter is equal to half the frequency separation between resonances. For this case, the cubic term in the response is zero. The next non–vanishing term in the series expansion for the response is fifth–order (All even terms are zero due to symmetry). The elimination of second and third order terms is a consequence of the symmetric nature of the absorption curves. One could thus have non–Lorentzian lineshapes, and have the same result, provided these curves were symmetric about their center frequency. However, if the absorption curves are not symmetric, then it is probably not possible to adjust parameters to achieve a condition in which both the second and third order terms are zero. Symmetric lineshapes are the norm for atomic species in a gas and for atomic defects in a solid. A gas cell detector would thus be one way of realizing this invention.

However, for high-frequency applications, where the modulation frequencies would be in excess of 1 GHz, and where the detector dimensions would hence have to be extremely small in order to collect the ionized electrons in a sufficiently short period of time, gas cells would be

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inadequate. In this case, a better approach would be to use an ultra-fast semiconductor photodetector having a broad optical spectral response, and to combine this detector with an optical filter having the desired narrow Lorentzian lineshape. Such an approach could be used for lower-frequency applications as well, and in fact would be the ideal way to produce an FM discriminator that would work over the entire zero to 60 GHz (or higher) frequency band, with the upper frequency limit being determined by the response time of existing photodetectors. This preferred approach is described below.

Referring to Fig. 4, a preferred embodiment is depicted wherein optical filters 32, 34 are inserted in front of respective semiconductor photodetectors 31, 33. Semiconductor photodetectors 31, 33 in this preferred embodiment have a spectral response that is much broader than the passbands of filters 32,34, depicted in Figs 5A and 5B respectively, so that the photocurrent vs. optical frequency characteristic of the filter-detector combination is determined by the filters alone. Optical filters 32,34 are fabricated to have a Lorentzian line shape. In fact, commercially available Fabry-Perot filters, (such as, for example, the fiber-optic Micron Optics FFP-TF series), in addition to having the desired line shape, can also be mechanically tuned for whatever wavelength one desires. One can thus adjust the wavelength separation between the two filters so that $\Gamma = \Omega$, insuring that one achieves the highest (maximum) linearity (Fig. 2A). An added advantage is that one can then readjust the filters to operate at other wavelengths. One device, therefore, can be manufactured that will satisfy a broad range of operating wavelengths, so that one could, for example, tune the discriminator to operate anywhere within the entire bandwidth of an Erbium doped fiber amplifier (1530-1560 nm wavelength). For very high-speed operation, the photodetectors of choice would, today, be InGaAs pin semiconductor devices. In particular, the use of fiber-optic filters together with dual-balanced, fiber-coupled detectors, such as the newly-developed NTT Electronics Corp NEL model KEPD2552KYG, would allow one to achieve greater than 20 GHz response using commercial off-the-shelf devices.

Those skilled in the art can appreciate that the present invention can also be practiced utilizing various alternatives to the embodiments described herein. For example, one could use individual photodetectors, connected to individual transimpedance amplifiers, and then subtract the two resultant signals with a differential amplifier to get the required difference signal. Further, one could attach the common point between photodiodes to a conventional RF voltage amplifier, and use the internal impedance (typically 50 Ohms) of the amplifier to convert the current into a voltage. Additionally, one could use other types of symmetric but non-Lorentzian filters to achieve cancellation of the third (or higher) order term(s).

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CLAIMS

1.   A method of optical frequency modulation discrimination, comprising the steps of:

splitting an optical beam having a frequency ω into a first optical beam having a frequency ω and a second optical beam having a frequency ω;

providing a first photodetector, the first photodetector providing a first current I_1 responsive to the first optical beam input thereon, the first photodetector having a first photodetector spectral response and being biased such that the first current I_1 is in a first direction;

providing a second photodetector, the second photodetector providing a second current I_2 responsive to the second optical beam input thereon, the second photodetector having a second photodetector spectral response and being biased such that the second current I_2 is in the first direction;

coupling an input of a transimpedance amplifier to an output of the first photodetector and to an input of the second photodetector to provide an output of the transimpedance amplifier proportional to the difference between the first current I_1 and the second current I_2; and

providing a first optical filter to receive the first optical beam prior to incidence upon the first photodetector and a second optical filter to receive the second optical beam prior to incidence upon the second photodetector,

wherein the first photodetector spectral response and the second photodetector spectral response are each broader than respective passbands of the first optical filter and the second optical filter to provide photocurrent vs. optical frequency characteristics determined by the respective first optical filter and the second optical filter.

2.   The method of optical frequency modulation discrimination of Claim 1, wherein the first optical filter and the second optical filter respectively provide Lorentzian line shapes.

3.   The method of optical frequency modulation discrimination of Claims 1 or 2, wherein the first optical filter and/or the second optical filter are tuneable to adjust wavelength separation

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between the first tunable optical filter and the second tunable optical filter to obtain maximum linearity.

4.   The method of optical frequency modulation discrimination of Claims 1 or 2, wherein the first optical filter and/or the second optical filter are tuneable to operate over a broad range of operating wavelengths.

5.   The method of optical frequency modulation discrimination of Claims 1 or 2, wherein the first optical filter and the second tunable optical filter are fiber–optic tunable Fabry–Perot filters and the first photodetector and the second photodetector are high–speed pin semiconductor photodetectors.

6.   An optical frequency modulation discriminator, comprising:

a optical splitter for splitting an optical beam having a frequency ω into a first optical beam having a frequency ω and a second optical beam having a frequency ω;

a first photodetector providing a first current I_1 responsive to the first optical beam input thereon from the optical splitter, the first photodetector having a first spectral response and being biased such that the first current I_1 is in a first direction;

a second photodetector, the second photodetector providing a second current I_2 responsive to the second optical beam input thereon from the optical splitter, the second photodetector having a second spectral response and being biased such that the second current I_2 is in the first direction;

a transimpedance amplifier having an input and an output, the input being coupled to an output of the first photodetector and to an input of the second photodetector to provide at the output of the transimpedance amplifier a current proportional to the difference between the first current I_1 and the second current I_2; and

a first optical filter located to receive the first optical beam prior to incidence upon the first photodetector and a second optical filter located to receive the second optical beam prior to incidence upon the second photodetector, wherein the first photodetector spectral response and the second photodetector spectral response are each broader than respective passbands of the

first optical filter and the second optical filter to provide photocurrent vs. optical frequency characteristics determined by the respective first optical filter and the second optical filter.

7.   The optical frequency modulation discriminator of Claim 6, wherein the first optical filter and/or the second optical filter are tuneable to adjust the wavelength separation between the first tunable optical filter and the second tunable optical filter to obtain maximum linearity.

8.   The optical frequency modulation discriminator of Claims 6 or 7, wherein the first optical filter and/or the second optical filter are tuneable to operate over a broad range of operating wavelengths.

9.   The optical frequency modulation discriminator of Claims 6 or 7, wherein the first optical filter and the second optical filter are fiber-optic tunable Fabry-Perot filters and the first photodetector and the second photodetector are high-speed pin semiconductor photodetectors.

10.   A method of optical frequency modulation discrimination, comprising the steps of:

splitting an optical beam having a frequency ω into a first optical beam having a frequency ω and a second optical beam having a frequency ω;

providing a first photodetector having a peak resonant absorption ω_1, the first photodetector providing a first current I_1 responsive to the first optical beam input thereon, the first photodetector being biased such that the first current I_1 is in a first direction;

providing a second photodetector having a peak resonant absorption ω_2, the second photodetector providing a second current I_2 responsive to the second optical beam input thereon, the second photodetector being biased such that the second current I_2 is in the first direction; and

coupling an input of a transimpedance amplifier to an output of the first photodetector and to an input of the second photodetector to provide an output of the transimpedance amplifier proportional to the difference between the first current I_1 and the second current I_2.

11.   An optical frequency modulation discriminator, comprising:

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a optical splitter for splitting an optical beam having a frequency ω into a first optical beam having a frequency ω and a second optical beam having a frequency ω;

a first photodetector having a peak resonant absorption ω_1, the first photodetector providing a first current I_1 responsive to the first optical beam input thereon from the optical splitter, the first photodetector being biased such that the first current I_1 is in a first direction;

a second photodetector having a peak resonant absorption ω_2, the second photodetector providing a second current I_2 responsive to the second optical beam input thereon from the optical splitter, the second photodetector being biased such that the second current I_2 is in the first direction; and

a transimpedance amplifier having an input and an output, the input being coupled to an output of the first photodetector and to an input of the second photodetector to provide at the output of the transimpedance amplifier a current proportional to the difference between the first current I_1 and the second current I_2.

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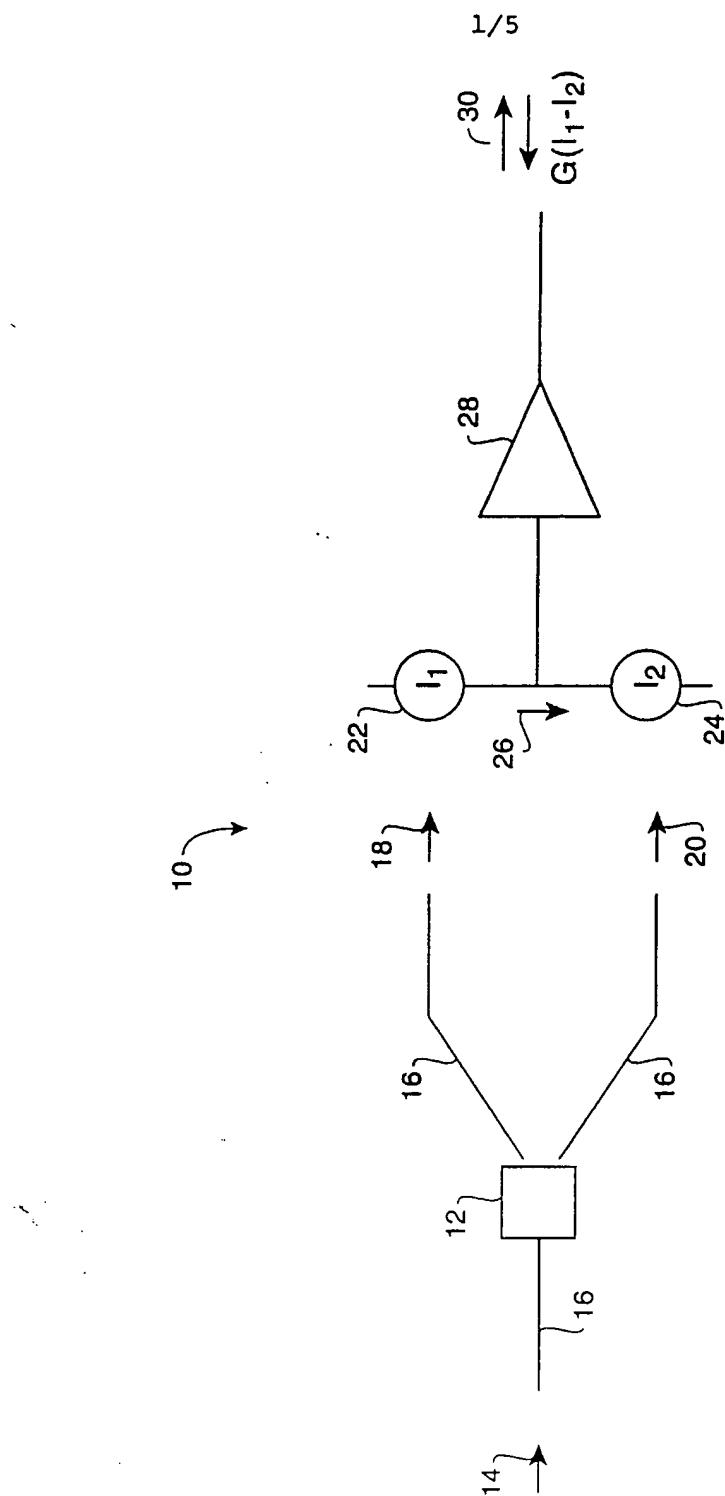
FIG. 1

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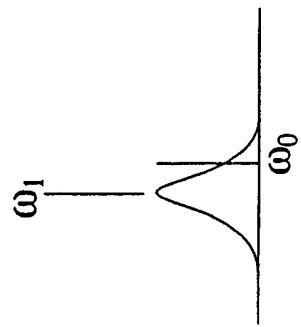
FIG. 2A
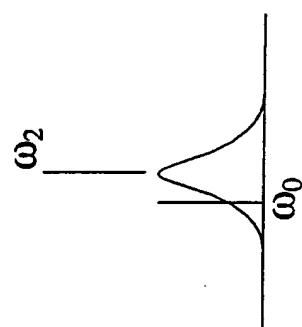
FIG. 2B
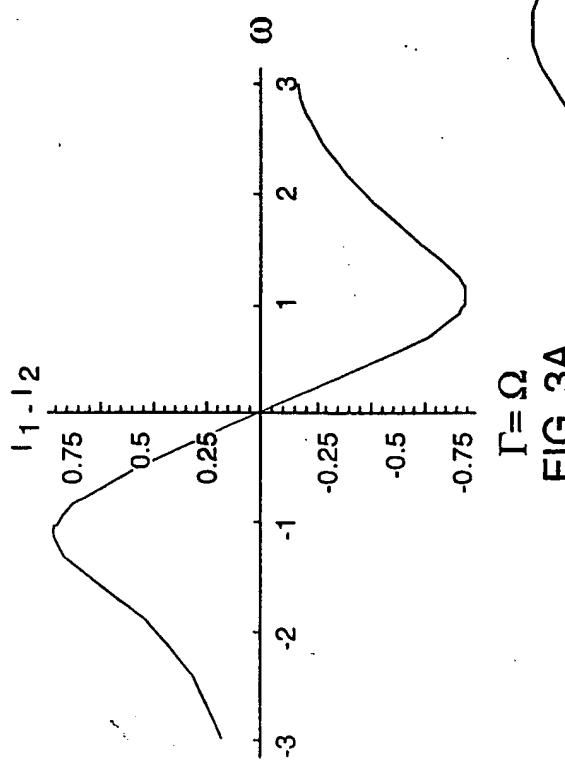
$\Gamma = \Omega$
FIG. 3A

$\Gamma = 0.5 \, \Omega$
FIG. 3B

$\Gamma = 2.0 \, \Omega$
FIG. 3C
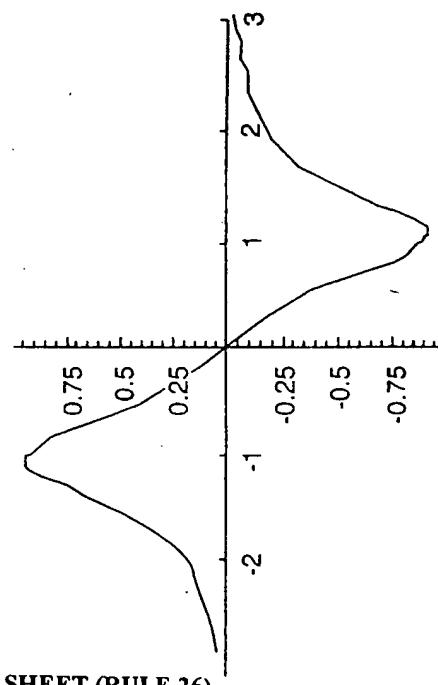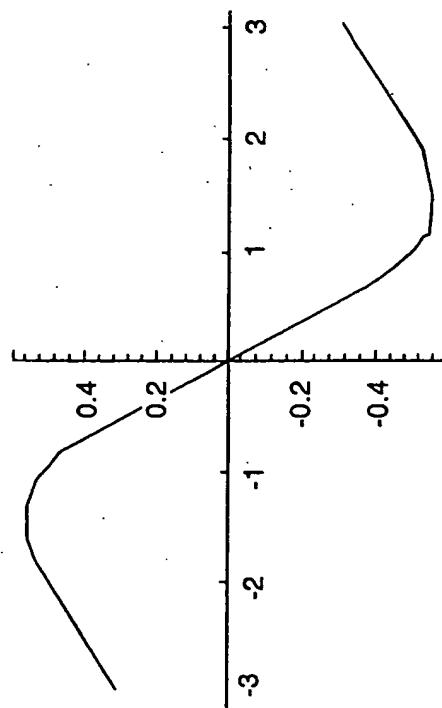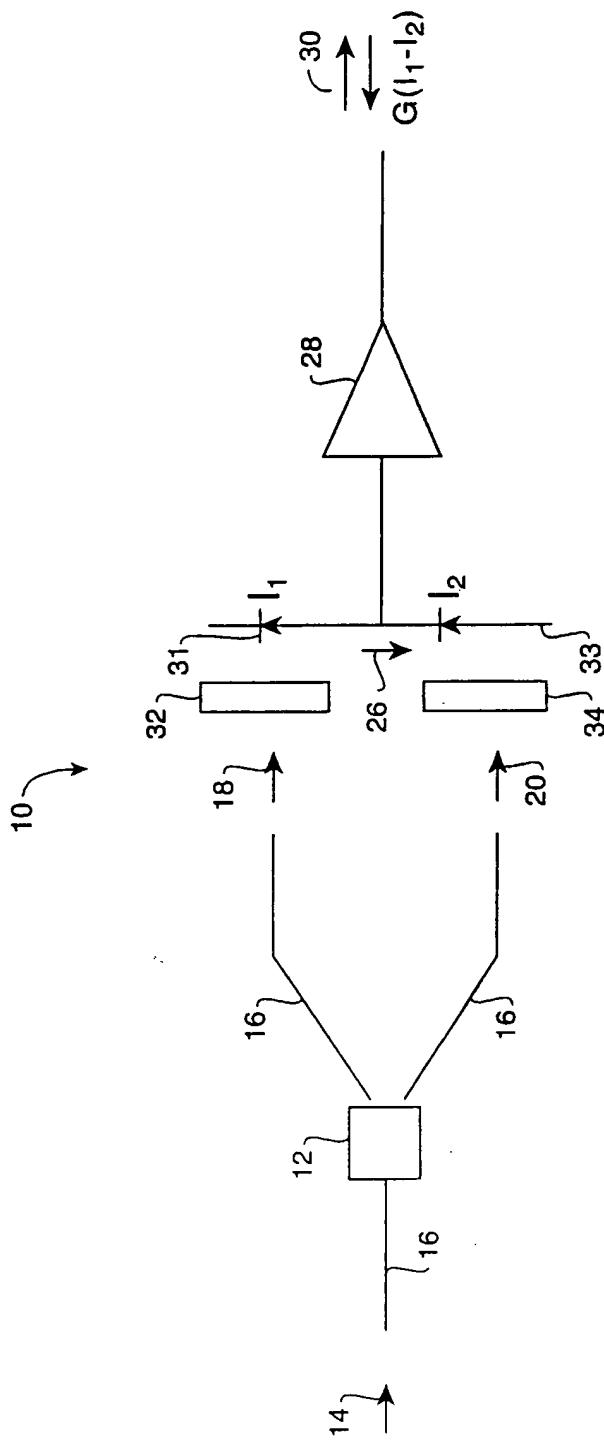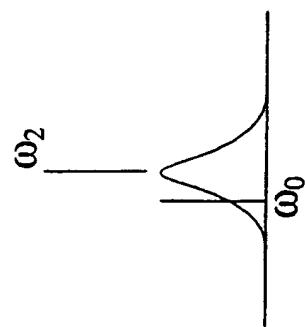
FIG. 4

FIG. 5A

FIG. 5B

INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 H04B10/158

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 H04B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, PAJ, WPI Data, INSPEC, COMPENDEX

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
P,X	WO 00 51271 A (MASSACHUSETTS INST TECHNOLOGY) 31 August 2000 (2000-08-31) page 4, line 5 - line 19 page 6, line 14 - line 20 figures 2,4,5A,5B	1-11
X	EP 0 591 866 A (CANON KK) 13 April 1994 (1994-04-13) column 11, line 9 - line 54 column 12, line 33 - line 42 column 31, line 23 - line 26 figures 5,6	1-11
A	EP 0 473 873 A (LANDIS & GYR BETRIEBS AG) 11 March 1992 (1992-03-11) abstract figure 2	1-11

☐ Further documents are listed in the continuation of box C.-   ☒ Patent family members are listed in annex.

* Special categories of cited documents :

'A' document defining the general state of the art which is not considered to be of particular relevance

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'P' document published prior to the international filing date but later than the priority date claimed

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'&' document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
22 November 2000	30/11/2000

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl. Fax: (+31-70) 340-3016	Reville, L

Form PCT/ISA/210 (second sheet) (July 1992)

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INTERNATIONAL SEARCH REPORT

In. .ustion on patent family members

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EP 0591866	A	13-04-1994	JP	6224882 A	12-08-1994
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